

SIXTH FRAMEWORK PROGRAMME



Project no: **502687**

NEEDS

New Energy Externalities Developments for Sustainability

INTEGRATED PROJECT

*Priority 6.1: Sustainable Energy Systems and, more specifically,
Sub-priority 6.1.3.2.5: Socio-economic tools and concepts for energy strategy.*

Deliverable T9.1 - RS2b

***Requirement analysis for
multicriteria analysis in NEEDS RS2b***

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Due date of deliverable: February 28, 2006

Actual submission date: June 30, 2006

Start date of project: 1 September 2004

Duration: 48 months

Organisation name for this deliverable:

International Institute for Applied Systems Analysis, Laxenburg, Austria

Project co-funded by the European Commission within the Sixth Framework Programme		
Dissemination Level		
CO	Confidential, only for members of the consortium (including the Commission Services)	X

Abstract

This report specifies the requirements for the NEEDS RS2b WP9 *MCDA Approach and Tool Selection*. It first summarizes the objectives of the Research Stream 2b in general, and of WP9 in particular. Then it provides a detailed specification of the problem to be subjected to multicriteria analysis; this includes the summary of the analysis context, discussion of the sets of criteria and alternatives, and the participation of the stakeholders. Next, the planned problem analysis process is first summarized, and then discussed in more detail through the presentation of use cases. Finally, the requirements for multicriteria analysis are specified. Additionally, the report contains characteristics of three energy applications that exploit the multicriteria analysis methods pertinent to the planned analysis in NEEDS RS2b.

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1 Introduction

1.1 Scope of this document

This document derives the requirements for the NEEDS RS2b WP9 *MCDA Approach and Tool Selection*. For this we summarize in Section 1.2 the objectives of RS2b in general, and of WP9 in particular. From these we derive in Section 1.3 the requirements for WP9, and the results of other Work Packages that are needed for WP9.

1.2 Objectives

The objectives summarized in this Section are taken from Annex 1 (Description of Work) of the NEEDS project.

1.2.1 Objectives of RS2b

The general objectives of the Research Stream 2b (RS2b) are:

1. To identify, discuss and analyze the terms and conditions for an effective formulation and implementation of long term energy strategies.
2. To broaden the basis for decision support beyond the assessment of external costs by examining the robustness of results under various stake-holder perspectives.
3. To contribute to the integration of results by other analytical tasks with the NEEDS project.

The specific objectives relevant to the WP9 objectives are:

1. To evaluate energy technologies and scenarios taking into account economic, environmental, and social criteria.
2. To investigate the sensitivity of the results of sustainability assessment to specific patterns in stake-holder preferences.

1.2.2 Objectives of WP9

The objective of WP9 is to select the MCDA (Multi-Criteria Decision Analysis) approach and software best suited for the purpose of NEEDS. When making this choice the arrangement of interactions with stakeholders needs to be taken into account.

1.2.3 Relevance of WP9 objectives to objectives of NEEDS

WP9 will directly contribute to attaining the specific objectives of RS2b summarized in Section 1.2.1, which requires the multicriteria analysis of large sets of alternatives characterized by a large number of criteria organized in a hierarchical structure. The criteria are diversified and conflicting, and are organized into three sets composed of economic, environmental, and social criteria respectively. Each of these sets has the hierarchical structure of the corresponding criteria. Moreover, different stakeholders not only have different preferences for trade-offs between such criteria, but also diversified backgrounds and thus experience in analyzing problems, and especially in defining preferences.

Therefore suitable MCDA methods and corresponding modeling tools are necessary for reaching the key objectives of the RS2b.

1.3 Content and structure of the requirement analysis

The remaining part of the report is organized as follows: Section 2 provides a detailed specification of the problem to be subjected to multicriteria analysis; this includes the summary of the analysis context, discussion of the sets of criteria and alternatives, and the participation of the stakeholders. The proposed problem analysis process is first summarized in Section 3, and discussed in more detail through the presentation of use cases in Section 4. Finally Section 5 provides a specification of the requirements for multicriteria analysis. Additionally, the appendix contains the characteristics of three energy applications that exploit the multicriteria analysis methods pertinent to the planned analysis in NEEDS RS2b.

2 Problem specification

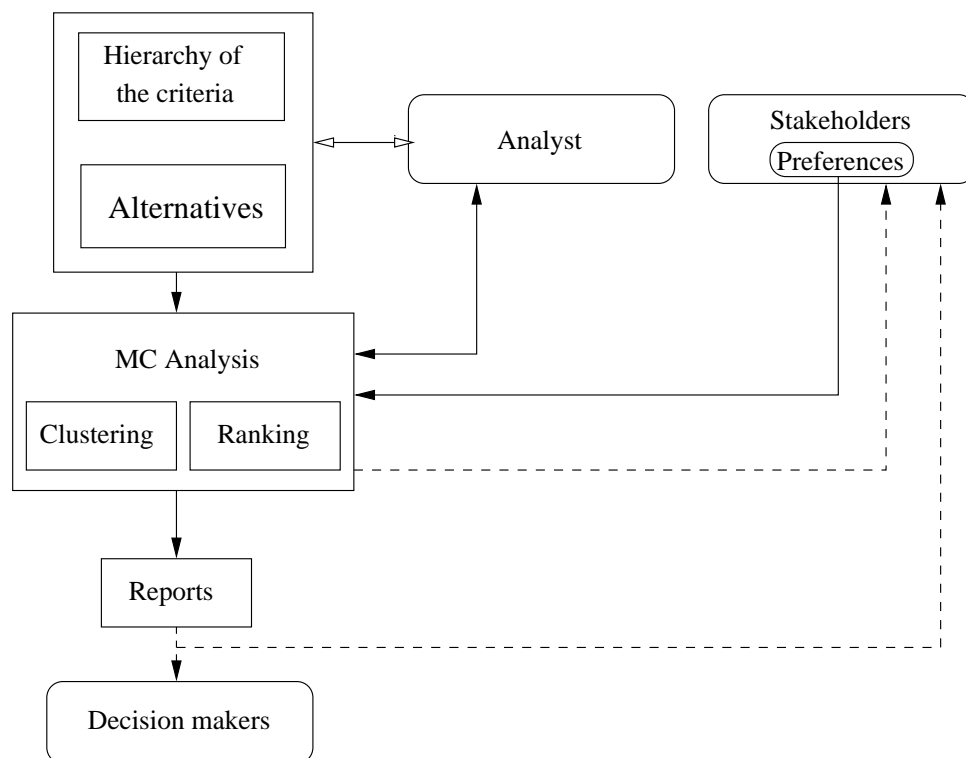


Figure 1: General structure of the problem analysis process.

This Section starts with a top-level summary of the problem for which one needs to propose and implement a methodology for multicriteria analysis.¹ The general structure of the problem analysis process is illustrated in Figure 1 and is characterized as follows:

1. A set of approximately 50 criteria (organized in an up to 4-level hierarchical structure) is given. The criteria are of two types: quantitative and qualitative.
2. Two sets of discrete alternatives will be given:
 - energy technologies (around 50)
 - energy scenarios (around 50)

¹The context of such an analysis is summarized in Section 2.1.

Each alternative is composed of an identifier and criteria values (either numerical or qualitative). The sets and structure of the criteria are the same for the two sets of alternatives (technology and scenario).

3. The preferences of diversified stakeholders will be elicited through surveys, and are expressed in terms which correspond to the criteria.
4. Analysis of individual preferences and the corresponding solutions will be done by experts in the energy domain in collaboration with experts in modeling and multicriteria model analysis.
5. The outcome of a multicriteria analysis of alternatives performed according to the preferences of each stakeholder will therefore be used by the experts for the second stage of analysis (and optionally provided to stakeholders through interactive Web-based surveys).
6. At least two types of outcome from the analyses are desired:
 - Information about alternatives (of technologies and scenarios, to be analyzed independently), each corresponding to a given representation of (individual) preferences; if possible this information shall include a ranking (full or partial, ordinal or cardinal).²
 - Clusters of technologies/scenarios, each matching a cluster (corresponding to a selected similarity measure) of the preferences of stakeholders.
7. The results of analysis will be presented in a report to be provided to stakeholders and decision-makers. Optionally, rankings corresponding to the individual preference of each stakeholder will be provided if the data will make a stable ranking possible.

Therefore, we actually deal with the problem of multicriteria analysis of two sets of alternatives to be done by experts (as opposed to multicriteria decision analysis done by decision-makers), who will include in the analysis the impacts of the diversified views of stakeholders.

From an analytical perspective the problem is characterized by:

1. A medium-size set of alternatives.
2. A large set of criteria organized in a hierarchical structure.
3. Criteria having diverse characteristics, including:
 - multimodal distributions of values,³
 - different types of criteria, i.e., numerical and ordinal.
4. A large number of diversified stakeholders with substantially different preferences.
5. The need for analysis reflecting, in a fair way, diverse preferences.

The remaining part of this Section is organized as follows: We begin with a summary of the context of analysis (Section 2.1) and follow with an outline of the elements of the analysis in Section 2.2. The sets of criteria and alternatives are discussed in Sections 2.3 and 2.4, respectively. The problem specification is completed by the discussion of issues pertinent to the stakeholders in Section 2.5.

²The availability of a stable ranking depends on features of data and preferential structure, therefore it is not possible to specify now which type of ranking will be possible.

³Roughly speaking, multimodal distributions are characterized by values split into several disjointed subsets separated by empty subsets covering large ranges of values. Consider e.g., two subsets of values: the first composed of positive values smaller than 100, and the second composed of values larger than 100000. Typical statistical characteristics of sets of values may not be adequate. For example, the value of an average is often far away from the closest value of a member of the set.

2.1 Context

2.1.1 The NEEDS Project, relevance to energy/electricity sectors and importance

The NEEDS project is intended to address the sustainability of electricity generation technologies and systems in a comprehensive, multi-criteria way. Task 2b of the NEEDS project focuses on the use of multicriteria analysis as an essential methodology that can assist individual decision-makers and groups in balancing the competing characteristics of different options in order to reach an option ranking in accordance with their preferences.

The electric industry is an important part of the overall energy sector for many reasons. Electricity serves as an energy carrier that transfers primary energy from many diverse sources to provide customers with a very wide range of end-user services. It is a uniquely flexible and high quality form of energy that is irreplaceable in many applications. Because of this it has an important and increasing share of the end-use energy market. The sheer scale of its use means that the electric supply industry has a very large infrastructure with a wide range of significant impacts in all three areas that traditionally comprise sustainability, i.e. the economy, the environment and society. Such impacts include internal and external costs to customers and society, environmental burdens like airborne emissions, toxic and nuclear waste and resource depletion, and an array of health, risk and safety considerations. The size and life of the infrastructure also means that the sector has a large inertia, so changes like the penetration of new primary energy sources can take a long time to make a significant impact. As one example, electricity generation is a primary contributor to CO₂ emissions, but it is susceptible to reductions by switching to low or zero carbon primary energy resources or carbon capture, more possible due to the relatively low number of large, fixed (non-mobile) sources.

NEEDS is intended to address the need to improve sustainability in the electricity sector by assessing a wide range of economic, environmental and societal indicators for a range of generating technologies, and to extend this technology-specific analysis to a limited number of scenarios for operating and expanding the electric sector in the future.

2.1.2 The MCDA problem as it applies to NEEDS

We use in this document the widely used term MCDA (Multicriteria Decision Analysis) because it covers a well developed field of OR (Operational Research) that provides methods and tools pertinent to our problem. However, we need to stress that our problem (described in detail below) substantially differs from typical MCDA problems (in which a decision-maker analyzes a decision problem together with his/her preferences). We deal with stakeholders and not with the decision-makers, and these two groups are fundamentally different and so are their goals. Thus the aim of the analysis of the problem under consideration is to find relationships between the preferences of diversified groups of stakeholders and corresponding solutions (technologies or scenarios). This analysis has some similarities with decision-making therefore we also briefly discuss here multicriteria analysis of decision-making.

Decision-making is difficult in the electric sector for many reasons. The scale of the problem is very large, the range of impacts is very broad, and the time-scales involved can range from seconds (or less) for operation to decades (or more) for planning. In particular, the scale of the planning problem means that it is a very important one for many people, and the broad range of impacts means that there are inherent trade-offs between competing characteristics (e.g. cost versus emissions) - which means that stakeholders are unlikely to agree. Different input assumptions, uncertainties and attitudes towards risk all further contribute to this disagreement. In particular, different groups such as utilities, regulators, customers and environmentalists all have different interests at stake (hence the term 'stakeholder') and their different points of view

lead them to have significantly different opinions on how different planning options should be ranked, or what may be the *best* strategy for system operation or expansion. To further complicate matters, no single decision-maker exists. Instead, there are decision-makers within each stakeholder group, and these groups interact within a public policy arena where negotiation and political processes are the rule.

The NEEDS project is intended to support this complex decision-making process primarily by supplying it with a common basis of trustworthy information. The MCDA task in NEEDS particularly helps decision-makers analyze technological alternatives and strategies, consistent with their preferences expressed in terms of the diversified set of criteria, in a clearly understandable and trustworthy way.

2.1.3 Why MCDA is needed

MCDA is intended to assist decision-makers in several different ways, according to the main problems experienced in making decisions on complex systems. In particular, the goal is to help make the decision-making process structured, explicit, clear and correct, so that not only is the ranking of alternatives right for each decision-maker's preferences, but the entire process serves as a clear basis for debate with others. Some of the typical problems are very briefly mentioned below:

Attainable goals: In order to make a good decision, it is necessary to specify preferences that lead to attainable goals (i.e., feasible values of criteria). This means it is necessary to clearly establish priorities and trade-offs between competing goals. MCDA assists in this by using clear procedures to establish preferences, and identifying a solution that best corresponds to the specified preferences.

Cognitive limits: Most people can make decisions between a limited number of alternatives, based on a limited number of criteria. But for large, complex systems our *instincts* are inadequate. This problem is exacerbated by mixing quantitative and qualitative indicators and preferences that are often discontinuous, non-linear, and have threshold values. MCDA provides an analytic structure that can clearly indicate why a given set of preferences (expressed in terms of criteria) results in a certain efficient solution; in some cases a certain ranking of alternatives can also be provided.

Preconceptions: It is typical for a decision-maker's initial preferences (expressed in terms of criteria) to result in a selection of alternatives that is inconsistent with the stakeholder's own preconceived characteristics of a solution. The stakeholder is confronted with the choice of modifying his/her expectations about the solution, or her/his preferences (or both) until a consistent result is achieved. Only multicriteria analysis can really demonstrate such inconsistencies, and assist in resolving them iteratively.

Group differences: It is rational for a heterogeneous stakeholder group to disagree, and often necessary for them to reach some joint decision. MCDA can clarify the reasons for disagreements and form a basis for discussions and negotiations. Some MCDA methods are also more formally combined with joint-resolution methods (although not in this project).

2.2 Elements of multicriteria analysis

Multicriteria analysis is composed of several interlinked elements, which do not form a linear process, i.e., some of them are developed in parallel, and/or can be modified during the analysis. We list these elements in the order in which they are discussed below:

1. Definition of criteria.
2. Definition of alternatives.
3. Preparation of the problem analysis.
4. Problem analysis composed of a sequence of two steps:
 - ★ a specification of user/stakeholder preferences, and
 - ★ finding a solution (an alternative, or a ranking of alternatives) best corresponding to the preferences.
5. Analysis of results.

The essence of multicriteria analysis is actually the sequence of modified preferences based on the analysis of solutions corresponding to previously specified preferences. The reason for such a sequence is the commonly known fact that typically, (especially in an initial stage of problem analysis) solutions corresponding best to preferences differ substantially from the expectations of the user. Therefore the user typically needs to modify his/her preferences in order to find solutions that are close enough to the goals (values of criteria) that are both attainable, and have trade-offs between criteria that fit the user preferences.

2.3 Set of criteria

Criteria are used for measuring the performance of alternatives. Therefore the choice of a set of criteria is of primary importance for the analysis of alternatives. The set of criteria to be used in the problem under consideration will be provided as the result of the WP13, therefore we only summarize here the main considerations taken into account by this study.

Main considerations that were taken into account for the choice of specific indicators:

- Results of a literature survey on sustainability indicators in general (past experience).
- Social indicators generated within a dedicated WP in a pioneering effort, which also included a Delphi exercise.
- Catching the essential characteristics of technologies and enabling differentiation between them.
- Assuring that indicators are representative (but not necessarily complete).
- Keeping the number of indicators at a reasonable level and striving for a certain balance in terms of the number of indicators.
- Trying to avoid excessive overlapping.
- Aiming at limited aggregation of indicators provided that this involves no or minimum subjectivity.
- Assuring practicability and feasibility; in particular having confidence that the indicators can be generated within research stream RS2b or will be available from other NEEDS research streams.

Important features of the proposed set:

- The selected indicators are distributed between the three sustainability dimensions, i.e. environmental, social and economic.
- The overall structure and selection made will be the subject of a stakeholder survey.

There are different types of indicators (e.g., quantitative and qualitative), at least some of them having a multimodal distribution of values. Based on past work on similar projects considering sustainability indicators, an expected number of criteria would be around 50. Such indicators are often divided into the *three pillars of sustainability*, i.e. those relating to the general areas of the economy, environment and society. Criteria are structured into a hierarchy (up to four levels within each of these three major categories). This structure is somewhat relevant to the ranking analysis, but more important to preference elicitation, where the addition of such a structure can give decision-makers a framework for weighing their preferences. For issues of

sustainability, 50 might also be considered a reasonable upper bound on the number of criteria, because adding further criteria dilutes the impact of those already present.

For each qualitative type of indicator a dictionary entry needs to be provided. Such a dictionary element is composed of:

- criterion name,
- descriptor/label,
- order – a (real or integer) number inducing an order within the set of admissible values of the corresponding indicator. It is assumed that the higher number corresponds to a higher preference. Partial order is allowed (i.e., duplicate values of the *order* attribute).

level 1 criteria	level 2 subcriteria	level 3 subcriteria	level 4 subcriteria	indicators	Units
Economy	Impact on customers	Impact on Electricity Price		Production cost	E/cents/KWh
	Financial risk & Flexibility	Risks	Liquibility	Degree of difficulty to sell a specific plant for fair price	Ordinal
			Risk due to volatility of fuel price	Increase in production cost resulting from fuel price doubling	factor
		Flexibility	Flexibility in economic use of available capacity	marginal costs	Eurocents/KWh
			Limitation of electricity production	Load factor	%
...					
Environment	Climate change			Global warming potential	kg(CO ₂ eq.)/kWh
	Wastes	Medium & High Level Radioactive Wastes to be stored in Geological repositories		total amount	m ³ /kWh
		Special chemical wastes stored in underground repositories		total weight	kg/kWh
...					
Social	Social & individual risks	Perceived risks	Perceived risks characteristics for normal operations	Subjectively expected health consequences of normal operation	ordinal scale
			Perceived risks characteristics for accidents	Psychometric variables such as personal control, catastrophic potential etc.	ordinal scale
	...				

Table 1: Illustration of hierarchical structure of criteria.

Table 1 only illustrates a part of the four-level criteria hierarchy, which actually has diverse depths (i.e., some branches of the criteria tree have only two or three levels). A specification of the criteria (including their hierarchical structure) will be provided in the report of WP13 of RS2b.

2.4 Sets of alternatives

Two sets of alternatives outlined below will be analyzed. Alternatives define corresponding sets of electric generation technologies which can be combined into a limited number of supply expansion plans or scenarios. The set of alternatives is broad enough to be interesting to all stakeholders, and specific enough that results are calculable. The definition of alternatives

includes both common and technology-specific assumptions (e.g., fuel prices and fuel efficiencies), system boundaries, etc.

The number of generation technologies considered will be around 50 alternatives. This can cover a range of technologies for the different fossil fuels, nuclear plants, and a selection of renewable generation options. The number of scenarios will also be around 50. Due to practical reasons it is desirable not to change the set of criteria and indicators for these two sets of alternatives. A more detailed discussion of these issues will be provided in the report of WP13 of RS2b.

2.4.1 Preparation of alternatives

Each alternative/object is described by values of criteria (often called indicators). Each criterion is either numerical (quantitative or cardinal) or non-numerical (qualitative or ordinal). The following table illustrates (in the form of a matrix) a data content for a set of m alternatives, each identified by an identifier (here defined as id_i) and characterized by values of n criteria (thus, the value of j -th criterion for i -th alternative is defined by $v_{i,j}$).

criteria alternative id	$crit_{erion}_1$	$crit_{erion}_2$...	$crit_{erion}_n$
id_1	$v_{1,1}$	$v_{1,2}$...	$v_{1,n}$
id_2	$v_{2,1}$	$v_{2,2}$...	$v_{2,n}$
...
id_m	$v_{m,1}$	$v_{m,2}$...	$v_{m,n}$

Two sets of alternatives (for technologies and scenarios) will be prepared. The values of criteria/indicators will be stored in the units defined for each criterion. The following convention is used for unavailable or infinity values:

- a single question mark denotes a missing value,
- the word INFINITY (or -INFINITY) denotes an "infinite" number (i.e., a number beyond the considered range of values).

No scaling/transformation shall be applied to the criteria values of alternatives during the data preparation and verification. Such transformations may be applied during the problem analysis.

2.5 Stakeholders

2.5.1 Context

Planning and decision making in the electric power sector should consider stakeholder preferences. Thus to achieve a reasonable quality of analysis (that will be a major factor in a decision-making process) it is critically important to adequately represent the stakeholder preference. However, this is not only important but also a very difficult issue because of the two sets of problems.

Firstly:

- The preferences are substantially different for different groups of stakeholders.
- Stakeholders typically do not have experience in the processes of formal analysis.
- Stakeholders have diversified backgrounds, thus not many of them will be able/willing to specify preferences for all criteria (that are specified on the lowest level in a rather detailed way).

- The rather short time period (between the set of alternatives being available and when the results of analysis are due).

Secondly, it is known (from the properties of the mathematical programming problem corresponding to any method of analysis of our problem) that:

- The relation between changes of preferences and the corresponding changes of solutions is nonlinear and discontinuous, i.e., in many situations even large changes of preferences do not result in (substantial) changes of solutions, while in other situations a very small change of preferences results in a qualitative change of a solution.
- Even for easier (from the mathematical programming view) problems (e.g., continuous linear models) preferences specified by stakeholders result in solutions inconsistent with his/her preconceived characteristics of the corresponding solution; such inconsistencies have to be resolved and this is only possible by either changing the preferences or expectations about a satisfactory solution. This is a typical situation, and the main argument for interactive problem/model analysis.

It is commonly agreed that elicitation of stakeholders preferences must include computerized interaction with each stakeholder during which she/he will be supported in the analysis of the correspondence between her/his desired goals and the corresponding attainable outcomes/results. However, it is also commonly agreed that designing and implementing an effective interaction is a challenging task. The challenge is caused by the fact that elicitation of preferences is based on a learning (about the problem) process, and in the case of many users/stakeholders this will be unsupervised learning. Thus the interaction must be carefully designed to address the needs and expectations of stakeholders with a wide spectrum of backgrounds and goals.

2.5.2 Information that should be provided to stakeholders

A stakeholder can be provided with two sets of information pertinent to specification of preferences:

- Common (for all stakeholders) composed of general information (about the problem, elicitation of preferences, etc.) and characteristics of the sets of alternatives. The latter should contain:
 - ★ a definition of each criterion/indicator,
 - ★ basic information regarding the value distribution of each criterion,
 - ★ basic information regarding the distribution of numbers of alternatives along values of each criterion,
 - ★ specification of the criteria structure,
 - ★ the pay-off table (best and worst values of each criterion),
 - ★ information about clusters of solutions corresponding to "selfish optimization" of each criterion.⁴

This information shall be developed as part of a Web site to be developed for on-line elicitation of preferences.

- Individual information corresponding to various preferences specified by the stakeholder. This information will enable a stakeholder to modify her/his preferences until a satisfactory solution is found, and should include:
 - ★ providing a solution corresponding to a specification of preferences,
 - ★ various ad-hoc information, e.g., number of feasible alternatives for lower bounds specified on values of a set of criteria,

⁴Best value of each criterion has an associated set of alternatives. Some of these sets are likely to overlap, and this might be interesting information.

- ✧ optional characteristics of classification/rankings of solutions corresponding to a set of preferences.

2.5.3 How is preference information used in a problem analysis?

In order to justify the proposed requirements for the elicitation of stakeholder preferences we need to summarize how preference information is used.

The preference information will be used to compute parameters of a scalarizing function. There is a class of formalized methods for model⁵ analysis that uses preference information for the calculation of parameters of a scalarizing function, i.e., a function that associates a number with each solution (an alternative in our case) that measures the quality (goodness) of the solution. For a multicriteria analysis such a function maps a multi-dimensional space of criteria into a one-dimensional real-number space which induces (at least partial) order in the solution space. Therefore, various multicriteria methods differ by:

- specification of scalarizing function,
- mapping of the preferences into parameters of the selected scalarizing function.

Thus, the properties of various methods of multicriteria analysis can be considered by examination of the properties of:

- the corresponding scalarizing function,
- the properties of sets of criteria values.

The latter is especially important for the analysis of discrete alternatives with multimodal distribution of criteria values.

Typical users do not consider mathematical properties of their problems. They reason in terms of trade-offs between criteria. Such trade-offs alter with changes of criteria values (e.g., a "weight" for costs is much higher for "expensive" alternatives than for "cheap" ones). Therefore specification of trade-offs is often done for a given solution rather than for the whole range of criteria values (e.g., how much more am I willing to pay for an alternative which has a lower emission of pollution). Moreover, users analyze the quality of a solution in terms of the acceptability of the values of criteria (e.g., is the cost within my budget?, is the emission level acceptable?). Hence, users focus on a subset of criteria whose values the user considers unsatisfactory, and try to improve them by changing preferences. Of course, by improving the value of even one criterion, the value of at least one other criterion will worsen, and this may be not acceptable, which in turn calls for another modification of preferences.

This short summary of the essence of multicriteria analysis shows that an interactive procedure is practically a must for a proper specification of preferences.

2.5.4 Preference information from stakeholders

Generally, the information provided by a stakeholder needs to be sufficient to represent his/her preferences in terms of criteria (e.g., as trade-offs between criteria values). As explained above, these trade-offs are typically different for various (1) ranges of criteria values (on the lowest hierarchy level for each group of criteria) and (2) ranges of a scalarizing function (for levels above the lowest level); therefore trade-offs differ for:

- Sets of ranges of criteria values (when specified for a subset of criteria at the lowest level in the criteria hierarchy). For example, trade-offs are typically different for:
 - ✧ expensive, medium-cost, and cheap solutions, and/or
 - ✧ large, medium, low emission levels.

⁵A set of alternatives can also be considered/represented as a model.

For expensive solutions (having low emission levels) a substantially stronger preference will be attached to the cost reduction than for cheap solutions. The corresponding preferences for emission levels will change in the opposite direction.

- Sets of ranges of a scalarizing function (when specified at levels above the lowest one).

There are several ways of dealing with trade-off specification. For our problem (characterized by large numbers of criteria and alternatives) approaches based on pairwise comparisons are not practicable. This reduces the choice of methods for trade-off specification to:

- Direct specification of weights (for criteria and for scalarizing functions).
- Indirect specification of weights, e.g., by specification of relative importance of criteria.
- Indirect specification of parameters of scalarizing functions by selection of:
 - ✦ aspiration (the desired criterion value) and reservation (the worst criterion value the stakeholder is willing to accept) values for each criterion, or
 - ✦ aspiration or reservation values for each criterion, and information about trade-offs between criteria at the selected aspiration (or reservation) point.

Additionally, the following preference information from stakeholders would be useful for a better support of the preference elicitation process:

- Specification of an acceptability (threshold/veto) level for criteria (equivalent for rejecting alternatives having worse values of the corresponding criteria).⁶
- Optional specification of sets of compensatory criteria. Criteria are compensatory when an increase of the value of one of them by a given value from a relative scale can be rationally substantiated to compensate a deterioration of another criterion.
- Optional specification of trade-offs between a selected subset of criteria (e.g., answering questions like *"if you want to improve the value of this criterion then select criterion/criteria you agree to worsen."*)
- Optional, based on intuition, selection of best and worst alternatives. This information will not be used for the representation of stakeholder preferences; it can be used in the final analysis of the problem, including various characteristics of stakeholders.

Moreover, for the second stage of analysis (to be done by analysts) some information about each stakeholder needs to be provided, e.g.: a category of the stakeholder.⁷

Elicitation of stakeholder preferences will be done through surveys described in Section 4.5.

3 Problem analysis

3.1 The purpose

The NEEDS project is aimed at influencing and supporting EU decision-makers who can influence expansion planning for the electric generation sector. The decision-makers need to make good quality decisions, consistent with their preferences, also taking into account the preferences of stakeholders. NEEDS is aimed at promoting decisions that will enhance sustainability in the electric sector, and ensuring that a quality information base exists to support these decisions.

The report summarizing multicriteria analysis will be a major factor in such a decision-making process. The analysis will be based on the stakeholder preferences which are expected to substantially differ amongst groups of stakeholders. Thus the analysis will attempt to fairly

⁶This approach appears to be a much better way of eliminating some alternatives, than to attempt to do so by playing with weights/reservations.

⁷This information may be provided by the organizers of the survey. However, additionally, stakeholders may be asked for a *"self-categorization"*.

account for these differences and may result in clusters of solutions corresponding to clusters of preferences. It is beyond the scope of work to attempt any type of analysis needed for supporting group decision-making process, consensus building, or negotiations.

The main target of the MCDA work package is to produce a multi-criteria based analysis of two sets of alternatives: a set of generation technology alternatives, and a limited set of system expansion scenarios combining these technologies.

3.2 Basic assumptions

The following assumptions about the analysis process have been agreed upon:

- Two parallel analyses (for scenarios and technologies) will be done.
- Two types of the multicriteria analysis will be performed:
 - ★ Analysis of alternatives corresponding to individual preferences of a stakeholder.
 - ★ Analysis of sets of solutions (technologies and scenarios) corresponding to the individual preferences of stakeholders.
- If the set of criteria for both (scenarios and technologies) analyses will be the same, then a provision should be made to facilitate the use of a specification of preferences from one analysis as a starting point in the other analysis.

3.3 Analysis based on preferences of a stakeholder

This analysis should be done by a stakeholder who will use a Web-based application supporting interactive multicriteria analysis of alternatives (using data provided by a data server, see Section 5.2).

The basic result of an analysis will be a Pareto efficient solution (either a technology or a scenario, for analysis of the set of technologies or scenarios, respectively) that corresponds best to the stakeholder preferences. Additionally some information can be provided about ranking of alternatives. However, due to the nature of the problem a ranking may not be stable, i.e., even small changes of preferences can result in rather different rankings. Actually, features of possible rankings strongly depend on the characteristics of the criteria values of the considered sets of alternatives, and the latter are not yet known; the actual characteristics of data to be used in our problem might be different. However, the note of caution (about the stability of rankings) is based not only on an example of data (of a similar type of problem) but also on the properties of sets of discrete alternatives analyzed, especially those having multimodal distribution of criteria values.

3.4 Analysis of results corresponding to stakeholders' preferences

This analysis will be done by PSI energy experts in consultation with IIASA modeling experts. The results of this analysis will be used for a report to be submitted to decision-makers and stakeholders.

The following types of analysis will be explored:

- Clustering of preferences (and possible correlations with categories of stakeholders) for various given (by the analysts) similarity measures.
- Analysis of possible correlations between clusters of preferences and clusters of the corresponding results.
- Analysis of distributions of solutions (technologies/scenarios).
- An attempt to find (possibly partial) rankings, if stable rankings are possible for the given sets of alternatives and stakeholder preferences.

Most likely the following results will be attainable:

- Clusters of solutions (technologies/scenarios) corresponding to clusters of preferences (the latter possibly correlated with clusters of stakeholders' categories).
- A partial ranking of solutions (technologies/scenarios) within clusters of solutions.
- Identification of a subset of "stable" solutions (those which are "typically" either "good/very-good" or "bad" or "in the middle"), and "jumping" solutions (which for small changes of preferences are either good or bad).

Given the known characteristics of the problem, and the expected data, the following types of analysis are unlikely to be possible:

- Aggregation of stakeholders preferences, and using them as "representative" preferences for multicriteria analysis of alternatives.
- Reliable rankings of solutions.

4 Use cases

This Section summarizes the way in which the problem will be analyzed. The structure of the analysis process is illustrated in Figure 2.

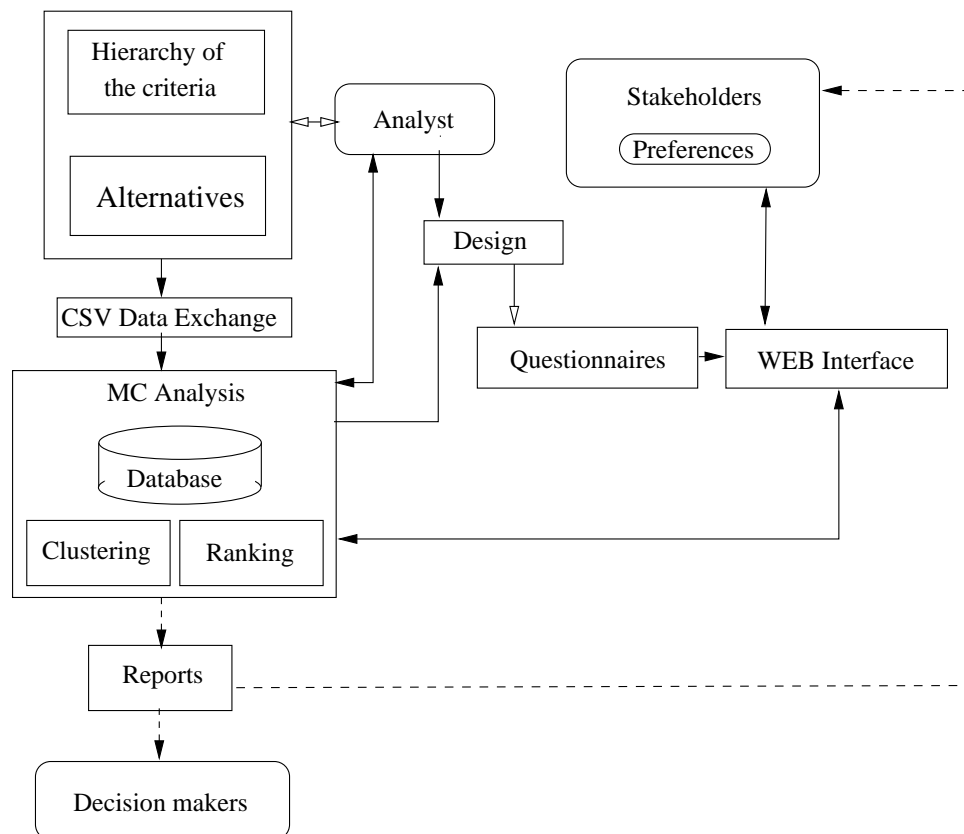


Figure 2: The main components of the process of the analysis of alternatives

The structure of this Section (after the General information) corresponds to the elements of the multicriteria analysis outlined in Section 2.2.

4.1 General information

- The analysis will be done independently for four countries (see Section 4.5 for details)
- For each country two sets of analysis will be done, for technologies and scenarios.

4.2 Set of criteria

The set (or parts of it) of criteria definition will be provided as the result of research of WP13 of RS2b, and will be prepared in a CSV⁸ text format, and will be uploaded to a data-server (see Section 5.2).

4.3 Sets of alternatives

The two sets of alternatives described in Section 2.4 will be developed by the collaborating WPs, then prepared in CSV format files, and will be uploaded to a data-server.

4.4 Preparation of the problem analysis

The set of criteria and two sets of alternatives will be uploaded to the data-server. While doing this the analysts will perform a consistency check of the data loaded to the data-server, and assure that the data providers correct the data before the preparation of questionnaires or before the elicitation of stakeholder preferences start.

The analysts will actively take part in the process of problem definition (definition of alternatives and criteria) as well as in the process of preparation of questionnaires. The analyst team will provide comments and feedback for the design of the survey, and will be responsible for the specification of information to be requested from the stakeholders.

The survey should be designed in such a way that the stakeholders will be able to observe in real time the influence of his/her preferences on the corresponding solutions, and then change his/her preferences until a satisfactory solution is found. Such a process supports learning about the problem during the specification of preferences. This approach has significant advantages over static questionnaires, and stakeholders should be motivated to use the Web interface. It should be stressed that most of the multicriteria analysis methods assume interaction with the decision makers or stakeholders. Therefore, the use of static questionnaires to elicit the preferences of the stakeholders has limited value in comparison to an interactive tool accessible by the Web interface, which in turn provides real-time access to a multicriteria tool operating on the data provided by the data server.

Moreover, for a Web-based elicitation of preferences the results can be stored directly in the database, and thus allow the stakeholder to optionally continue the analysis later. Web-interface also provides efficient ways of designing user-friendly surveys, including context sensitive help and tutorials.

4.5 Elicitation of stakeholder preferences

An appropriate elicitation of stakeholder preferences is typically difficult but – as discussed in Section 2.5 – it is especially challenging for the problem described in this report. Therefore we provide here a much more detailed (than for other elements of the analysis described in this Section) justification and description of the process.

⁸Coma separated values.

The communication with stakeholders is extremely difficult because there is a gap between information that is required by the analysis method and the language in which the problem is communicated and understood by stakeholders. Therefore, the communication method is a key element in gathering the proper information from the stakeholder, using it in the decision process and communicating the results of the decision. Moreover, a process of preference specification is not stationary, i.e., even very experienced users of multicriteria analysis tools change their own preferences in a rather discontinuous/erratic way. Therefore it is important to repeat here the arguments presented in Section 2.5 which justify the need for an interactive (repetitive) process of elicitation of preferences. This is a necessary condition to acquire a reasonably good representation of stakeholder preferences.

Therefore it is assumed that the elicitation of stakeholder preferences will be done via a Web-based interactive survey/questionnaire, which will provide diversified characteristics of a solution corresponding to a current specification of preferences, and will help (by providing pertinent information) to modify the preferences in a way that the next solution will better fit the expectations/preferences of the stakeholder.

Given the number of stakeholders planned to be surveyed, and the tight time-table of the whole project (which will leave a rather short period of time between the alternatives being available and the results of the surveys being due) a Web-based survey directly linked with a data server appears to also be a reasonable solution from the point of view of the whole project management.

4.5.1 The survey questionnaire

The design, implementation, and execution of the preference elicitation for the MCDA task will be a significant part of the overall task effort. The following items describe the expected scope, design, validation, analysis and use of the preference survey.

- **Survey size** - It is expected that the total number of stakeholders to be surveyed will be at least several hundred in each of four countries. These countries and the institutes responsible for selecting the survey participant list are as follows:
 - ★ Switzerland: The Paul Scherrer Institute expects a survey list of approximately 500, based on existing mailing lists for related purposes.
 - ★ France: The survey list is to be composed jointly by the French utility EDF and an independent non-governmental organization (NGO).
 - ★ Germany: The survey list is to be composed by the Fraunhofer Institute.
 - ★ Italy: The survey list is to be composed by ISIS.
- **Survey form** - Due to the large number of stakeholders to be surveyed it is clear that it will be impossible to perform individual preference elicitations, either in person or by phone. This means that as many as possible stakeholders should use an interactive Web-based survey, which will not only provide a qualitatively better elicitation of preferences but will directly store the results in a data server. Survey list selection should emphasize the likely commitment to respond, as well as other factors. Survey design will be important, and may justify consulting specialists for assistance.
- **Scope of survey** - Limitations on survey length due to response rates can have two effects on the choice of multicriteria analysis method. It would be desirable to use more than one multicriteria method on the alternative and preference data, in order to compare how well the different rankings corroborate each other. However, this means that the survey must include elicitation of preferences needed by both analysis methods.

- **Initial survey** - Any full preference survey must use a set of previously chosen criteria.⁹ Project personnel have expertise in the selection of such criteria, and experience with sets of sustainability criteria used for other projects. However, it would be useful to perhaps perform an initial survey of a subset of stakeholders to check whether an initially selected list of criteria meets with their approval, and whether they may suggest additional relevant criteria.
- **Full survey validation** - As noted above, the number of intended stakeholder participants requires the use of a Web-based interactive survey. However it is possible that it would be desirable to validate the survey as designed by conducting a limited number of phone interviews to check for any difference in preferences revealed by the survey. This could be done (preferably) as a confirmatory step following the initial questionnaire design with a subset of respondents, or as a follow-up after the full survey.
- **Preference analysis** - the Web-based survey will provide an interactive analysis of alternatives, thus not only assuring a qualitatively better elicitation of preferences, but also providing a valuable incentive to complete the survey which will assure a consistency between the specified preferences and the resulting Pareto-efficient solution.

4.6 The problem analysis

The analysis process will depend on the selected methods of multicriteria analysis, which will be described in [3]. Therefore here we only outline the major elements of the analysis.

The proposed analysis of the problem will be organized in three stages:

1. Preparatory analysis of alternatives:
 - Analysis of the values of criteria/indicators for alternatives. This analysis will provide distributions of the criteria values in each set of alternatives.
 - Analysis of the correlation between various criteria and groups of criteria. This can help in elimination of the criteria that are not important for ranking of the alternatives.
2. Individual exploration of solutions (technologies or scenarios, for analysis of the respective alternatives) corresponding to the preferences of each stakeholder. If properties of data and the preferences specified by a stakeholder will allow to determine a stable ranking (either partial or full, ordinal or cardinal) then such ranking will be provided. Such analysis will be supported by multicriteria algorithms for selection and ranking of alternatives best fitting the preferences of individual stakeholders. These algorithms might be used in two modes:
 - on-line generation of rankings of alternatives for stakeholders during the process of providing individual preferences;
 - analysis of the problem by the analyst; in this case the analyst can select an alternative algorithm or can specify some of the parameters of the algorithm.
3. Analysis of the results obtained from the multicriteria algorithms applied to preferences of individual stakeholders. This analysis will be done by the analysts to provide a basis for the final report, which will be submitted to decision-makers and to stakeholders. The clustering algorithms will be applied for the identification of groups of stakeholders with similar preferences, and for clusters of the corresponding solutions. Finally, an analysis of the characteristics of clusters of solutions will be made to detect if rankings can be established for at least subsets of solutions (technologies or scenarios).

⁹The set of criteria has been developed by WP3 of RS2b.

5 Requirements for multicriteria analysis

5.1 Requirements for the multicriteria analysis methods and tools

The following requirements should be met by the proposed multicriteria analysis method, and its implementation:

Ease of use: The method/tool will be used by both stakeholders (who are typically not experienced in analytical tools) and experienced analysts. Therefore specification of preferences has to be done in terms that are understood without knowledge of operational research. Also explanations of all pertinent terms (used for specification of preferences, and for the definition of criteria and alternatives) have to be easily accessible through hyperlinks in the Web-based survey. Moreover, preferences should be specified through a user-friendly interface. Finally, for the Web-based survey, at least a Pareto-efficient solution corresponding to the specified preferences should be easily available; preferably, assistance in assessing trade-offs between criteria should also be provided.

Transparency: Transparency focuses on the two elements of clarity (easy to understand), and trustworthiness. These both follow along the analytic chain, so it should be easy to see and trust:

- the input assumptions for the analysis of alternatives,
- the analytic process (e.g. the modeling methodology),
- the multicriteria analysis method.

Treatment of preferences: A stakeholder should be confident that the analysis method conforms to the form of his preferences, not the other way around. Preferences for thresholds, vetoes, non-linear scalarizing functions, etc. should be addressed.

Ease and speed of iteration: Using the method and the corresponding tool should be a learning process, and the first specification of preferences should be the start of an exploration process. If the iteration process can be quick and interactive, then the stakeholder will be more satisfied and motivated to spend more time in refining and verifying his/her preferences.

The following, more specific criteria, shall also be considered:¹⁰

1. Is method/tool available or does it require a limited amount of adjustments and tests?
2. Availability (free or license, restrictions, price).
3. Has method/tool been successfully used for energy applications relevant for NEEDS?
4. Simplicity, transparency, easy to use, interactivity.
5. Mathematical correctness.
6. Internal consistency checks.
7. Suitable for large amount of applications.
8. Processing, analysis and presentation of results.
9. Sensitivity analysis capability.
10. Compatibility with the intended elicitation of preferences.
11. Possibility to use “*simulated*” typical preference profiles.
12. Expandability in the future.
13. Can minority views be considered?
14. Non-discriminatory treatment of technologies.

¹⁰It is clear that there is no method which conforms to all of these criteria.

Moreover, one has to decide on using one or two multicriteria analysis methods. There are advantages and disadvantages in both cases. However this issue cannot be resolved before a representative sample of data is available. Therefore it is proposed to plan for the use of two methods, at least in the sense that we prepare for and implement this, but with the option that one method may be abandoned.

5.2 Infrastructure for the multicriteria analysis

The many participants of the analysis process (collaborating WPs, stakeholders), the serious time constraints (short time between availability of data and required output), and the many diversified data flows involving various teams implies the necessity for an efficient computing infrastructure.

Depending on the final selected method, the required computing resources may be substantial (especially, if many stakeholders perform interactive analysis simultaneously); therefore it is desired that there is the possibility for the easy use of a computational grid when a peak of computations occurs. Such a computational grid can be based on SGE (Sun Grid Engine) and a network of unix workstations.

It is not clear yet, how many computing resources will be needed for the on-line evaluation of preferences. However, it is clear that data handling poses a serious challenge unless an effective data server is provided. The most rational solution is a Web-based data server handling all data necessary for the analysis:

- Definition of criteria, including all necessary dictionaries, see Section 2.3.
- Alternatives (uploaded by either PSI or by collaborating WPs, versioning and automated documentation needed).
- Data needed for Web-based survey of stakeholders.
- Representations of stakeholder preferences (updated through the Web either by directly linking the survey forms with the DB, or by a dedicated interface to be used by staff processing paper surveys); versioning and automated documentation needed.
- Providing data for MC tools through either a direct link to the DB or upload/export of data from/to CSV files.

Such a data-server should be implemented using modern technology for the development of Web-based and distributed applications, and be based on a transactional professional database.

6 Conclusions

The report provides a comprehensive analysis of the requirements for the multicriteria analysis of technologies and scenarios to be performed at a later stage of the RS2b research stream. The analysis clearly shows that the problem is far more complex than recognized during the planning of the corresponding research. In the planning stage it was assumed that it would be possible to select one of many existing methods and tools for multicriteria analysis of sets of discrete alternatives.

The report provides a comprehensive specification of the problem, and the corresponding analysis process, which is the basis for another report that deals with characteristics of the available multicriteria analysis methods and tools, and assesses their applicability to the considered problem.

A Selected applications of MCDA to energy planning

A diverse array of multicriteria analysis methods have been widely applied to various types of energy problems. Section A.1 provides here a brief overview of applications in the energy planning area, including a brief classification, literature review and discussion and Sections A.2 through A.4 present three selected case examples of prior multicriteria analysis of energy problems. These examples illustrate the applications of three multicriteria methods that are pertinent to the needs of RS2b.

A.1 Prior MCDA applications in the electric and energy sectors

MCDA has a broad history of use in both the electricity and energy sectors. Both fields offer rich opportunities for a variety of modeling and optimization methodologies. The problems in these fields are complex and multi-dimensional, meaning that modeling or optimizing based on any one criterion (including least cost) is readily seen as overly simplistic. Therefore MCDA has often been applied either as an endogenous optimization function or as a post-analysis method of ranking results. MCDA has typically been used on an ascending scale with three main levels, including the following.

Technology choice: This is typically in the area of generation technology choice for either a generic or specific site. A broad range of criteria apply, but interaction with the rest of the electric system is ignored.

Electricity sector models: Modeling the electricity system means an integrated analysis of how different technologies are combined to meet shifting demand over time. The classic use is system dispatch modeling, which optimizes plant operation based on the variable dispatch cost using either a load duration curve or hourly operation approach. Dispatch modeling may be used tactically over the short term to model operation of an existing system, or for strategic planning over the long term to model system expansion. Some related, subsidiary electricity-related uses of MCDA emphasize the modeling of competitive markets and deregulation, emissions control policies and costs and transmission and distribution. Many electricity models ignore demand-side issues and price feedback on demand.

Energy sector models: Energy models include electricity as one sub-sector of the wider energy sector. They are generally based on a broader, higher level, including

- Substitution between different primary energy resources.
- Specification of end-use technologies with competition/substitution-Incorporation of price feedback on demand.
- Aggregation on a national, regional or global level.

Such models may use simulation or optimization over successive time periods, and again the MCDA may be either endogenous to the modeling or exogenously performed upon results.

A.1.1 Literature review

A literature review of MCDA applications was conducted, focusing largely upon electricity and energy related uses within 1) the Swiss research library search service NEBIS, and 2) an online MCDA bibliography database maintained at the University of Auckland in New Zealand.¹¹

¹¹<http://www.esc.auckland.ac.nz/people/staff/mehr002/References>.

Other reviews of MCDA applications in energy planning were also surveyed, see e.g., [1, 4, 5, 7, 9, 10, 11].

These various sources show that within three main levels of technology, electricity and energy indicated above, MCDA methods have been applied to a wide range of specific topics, including the following areas (the number in brackets indicates the number of specific papers surveyed).

Energy sector topics:

- General Energy Planning & Policy (24)
- Project, location or technology specific planning (12)
- Expansion planning (6)
- Emissions related (3)
- Transmission & Distribution (2)
- Deregulation/competition (1)

Electric sector topics:

- Strategic expansion planning (10)
- Dispatch/scheduling (9)
- Transmission & Distribution (7)
- Competition & deregulation (2)
- Emissions reduction (2)

The NEEDS project falls within the area of expansion planning, specifically the choice between many different generation technologies and several different system expansion scenarios, based upon sustainability considerations. As can be seen, papers dealing with expansion planning are a minority of the topics surveyed. The following discussion focuses on describing methods used in expansion planning, or used in related areas and suitable for such use.

The literature review reveals that a primary dichotomy within the area of expansion planning is between those methods that endogenously optimize the choice of technology or scenario, and those methods that choose between discrete or predefined alternatives. The optimizing approach appears more dominant in the literature, but this may be less true in real-world applications as publications may tend to over-represent more theoretical approaches.

A range of mathematical programming techniques have been used for endogenous optimization. Linear programming (LP) and mixed integer-linear programming (MILP) appear to dominate this area, but other methods include various goal-seeking approaches, including distance minimization or aspiration/reservation techniques. It is important to distinguish between the optimization technique involved and the way that the multicriteria approach is formulated into the objective function of the technique. For example, both LP and MILP techniques have a linear formulation of the objective function, which implies a linear tradeoff between the different criteria (the integer restriction of some variables for MILP is part of the constraints and not the objective function). This linear formulation may imply¹² a weighted sum approach to the MCDA; this is often cost minimization with pricing of non-economic criteria, or can be formulated as the weighted sum of expected values or expected utility functions.

The mixed-integer linear programming approach is often chosen because of the integer-number nature of building a new generation facility (i.e., it is impossible, or at least undesirable, to build only part of a new plant).

¹²This depends on the type of the scalarizing function. For example, reference point approaches use a non-linear scalarizing function, which however can be converted to a linear problem. Therefore an LP/MIP approach does not imply a weighted sum approach.

While it is not generally explicit in the literature, it does appear that for some optimizing techniques (e.g. LP and MILP) the application of the tool (or model) to the energy or electricity sector came first, and the MCDA elements were added later as a way of expanding the tool to incorporate other additional criteria. This is an evolutionary approach to using MCDA. The use of MCDA in the energy and electricity sectors also has trends in development, which include combining different MCDA tools or methods (e.g., Promethee and AHP or the use of fuzzy logic in many different approaches).

Applying multicriteria analysis to a set of discrete options typically aims not only at finding an optimum but also at providing various characteristics of pre-defined alternatives, typically ranking or classification or clustering of alternatives. The literature shows that the weighting approach is very popularly used in the electric sector for discrete rankings, as well as for the optimizing approaches described above. Overall, the weighting approach is fast, easy to understand, and flexible, allowing the incorporation of utility and risk elements. It does have drawbacks however (e.g., eliminating one option may cause the ranking of the remaining options to change). More detailed discussion of the features of the weighting approach is provided in [3].

The other main school of ranking evident in energy applications is the French school, including the family of Electre models (Electre I, II, III and IV, Electre IS and TRI) and Promethee. These models use the twin elements of concordance and discordance (or conjunction and disjunction). The concordance procedure allows a ranking of alternatives based on their positive elements, and the discordance procedure down-rates alternatives that are particularly bad on some (one or more) criteria. The 2D graph produced on the concordance/discordance axes gives a visual representation of which alternatives do well on many criteria and poorly on few, but a definite and unique ranking is not produced. The literature indicates that these models are more frequently used for screening alternatives as acceptable or unacceptable within a hierarchical framework of needs than for a cardinal ranking.

In addition to the concordance/discordance method, several other MCDA screening methods are available, including dominance comparisons, maximin/minimax comparison (risk averse), maximax comparison (risk positive), and lexicographic elimination. These methods are not used to produce cardinal rankings, so while their presence in the literature is noted, they are not suitable to the present NEEDS needs in the electric sector.

A.2 CETP (China Energy Technology Program)

Members of the NEEDS Task RS2b team have applied MCDA methods in a number of past projects, but one in particular illustrates the way that several screening and ranking approaches can be used together to provide a richer MCDA perspective. The China Energy Technology Program was a large project that used state-of-the-art techniques to apply sustainability criteria to electricity sector planning in Shandong province, China.

From the electric system modeling perspective, the CETP project consisted of automated, repetitive simulation of electric power system dispatch using a model called EGEAS (Electric Generation Expansion Analysis System). A large number of scenarios (18,144) were defined using stakeholder inputs. Specific alternatives were combined to produce 1008 strategies that were modeled under a range of specific uncertainties producing 18 different futures. Strategies specifying a mix of different new generation technologies were implemented using a model called PSP (Pre-Specified Pathway) to schedule the construction of individual plants. EGEAS was used to simulate least-cost system dispatch to produce plant generation, fuel consumption, plant and system costs and pollution emissions. These results were combined with results from other tasks that modeled life cycle burdens, emissions transport and damages, and risk and

safety factors to produce a wide range of sustainability indicators for each scenario. MCDA methods were applied to these results in three main different ways.

A.2.1 Multi-scenario, multi-attribute tradeoff analysis

The repetitive simulation approach applied in CETP does not optimize for the "best" solution, but rather "maps out" the option space available. The results are compared using interactive computer graphics to datamine the mass of results produced. In particular, tradeoffs between different pairs of criteria are examined to find patterns due to the effects of specific scenario options and uncertainties. These patterns showed the interactions between old and new capacity, fuel choices and operation alternatives (like early retirement or pollution control retrofits). The same software used for interactive statistics was also used to present the results to stakeholders, emphasizing strategies that were robust and flexible. This was a MCDA screening application that allowed stakeholders to reject dominated strategies and focus upon the tradeoff set of Pareto optimal strategies for key tradeoff pairs, in particular cost v. SO₂ emissions.

A.2.2 Concordance/Discordance MCDA analysis using stakeholder preferences

To assist the stakeholder decision-makers participating in these projects, a second phase of MCDA was used for deeper analysis of a subset of 12 selected scenarios. The concordance/discordance MCDA model ELECTRE III was selected for this analysis, and stakeholder preferences were gathered using individual interviews. The concordance/discordance method did not produce a simple ranking, but rather a 2D mapping of which strategies performed consistently well versus occasionally poorly.

A.2.3 Interactive weighted average MCDA for DVD presentation

The results of the CETP project were published in a book that included an accompanying DVD presenting the project's structure, assumptions and results. This DVD included presentation of both the screening and Electre methods described above. However for this purpose, a simple method of MCDA was also desired that could be interactively used to elicit preferences and present the user with rankings of individual generation technologies and simple combined strategies. The weighted sum approach was chosen for this purpose, and programmed in Macromedia Flash. This approach required some simplifications of system dispatch, emissions transport and other factors, but it also allowed individual users to experiment and learn about the implications of their own choices.

The experience gained in CETP indicates the strong value of using and comparing more than one method of MCDA analysis. This definitely requires a commitment of time and effort, but it also prevents undue confidence in a single method requiring subjective inputs (as all MCDA methods do).

A.3 MARKAL goal programming formulation

MARKAL is a large energy-economy model that covers the entire energy sector, including the electricity sector. Many different versions of the model exist, with a large user community that employs them for national, regional and global studies involving scenario analysis of energy economics, the environment, etc. MARKAL itself is used to formulate or structure energy questions, and its output passes to a solver engine that actually computes the solution to the stated problem. MARKAL models the full energy sector, including competing primary fuels (coal, oil, gas, uranium, wind, etc.), energy transport and conversion (i.e. primary energy to an

energy carrier like synthetic fuels or electricity), and competing end-use technologies that supply energy service demands (for heat, light, transportation, etc.). Although MARKAL models represent the entire energy system, some versions focus in more detail on the electricity sector or other areas like synthetic fuels and transportation. While originally a linear programming model, some formulations of the MARKAL family add non-linear elements and/or demand elasticity.

MARKAL's objective function was originally simple cost minimization, and the cost of emissions constraints were given by shadow prices. MARKAL has been expanded in many cases to consider multiple criteria by adding them to the objective function, implicitly monetizing them (e.g., carbon taxes). However MARKAL can also use an objective function formulation that is goal seeking. This means that rather than putting monetary weights on non-economic factors, the model attempts to minimize the distance in vector space from a given multi-criterion goal state.

A.3.1 The substantive model

The equations below show the model formulation for one goal-seeking version of MARKAL [2].

$$q_1 = \sum_{t \geq gpstart, e \in GPENV} ((1/cap_{e,t}) * escal_e * (ewt_e^- d_{1e,t}^- + ewt_e^+ d_{1e,t}^+))$$

$$q_2 = \sum_{t \geq gpstart} ((1/least_cost_e) * cscal_e * (cwt^- d_{2t}^- + cwt^+ d_{2t}^+))$$

$$TSC = \sum_{i,t} c_{i,t} x_{i,t} \epsilon$$

$$\sum_i a_{i,t} x_{i,t} \leq b_t \quad \forall t$$

$$\sum_{e \in GPENV, j \in F} e_{e,f} x_{e,t} - f_{j,t} + d_{1e,t}^- - d_{1e,t}^+ = cap_{e,t} * (1 - cappct_e)$$

$$\sum_i c_{i,t} x_{i,t} + d_{2t}^- - d_{2t}^+ = least_cost_t$$

$$x_i, b_i, d_1^-, d_1^+, d_2^-, d_2^+ \geq 0$$

where:

- $c_{i,t}$ - cost associated with each component or technology i of the energy system for time period t
- $a_{i,t}$ - matrix coefficient associated with each variable and row in LP representation of the energy system
- b_t - the right hand side of the equations of the LP for period t
- $e_{e,f}$ - emission coefficient associated with the technologies/fuel types in the energy system
- $x_{i,t}$ - variables associated with each component of the energy system
- q_1 - shows the total emissions over time,
- q_2 - denotes the total discounted costs over time.
- TSC - defines that the total investment over time must sum to the total cost TSC, and the remaining equations reflect system structure, emissions and costs.

A.3.2 The preference structure

The preference structure expressed in the objective function is to minimize s defined as:

$$s = q_1(\text{cap}_{e,t}, \text{escal}_e, \text{ewt}_e^-, \text{ewt}_e^+) + q_2(\text{least_cost}_e, \text{escal}_e, \text{cwt}^-, \text{cwt}^+)$$

with the following given parameters:

escal_e - scaling factor for each emission

cscal - scaling factor for total cost

ewt_e - weighting factor, above/below, for each emission

cwt - weighting factor, above/below, for total cost

$\text{cap}_{e,t}$ - emission levels from the reference case

least_cost_t - cost of least cost solution from the reference case

gpstart - year from which the GP emissions & costs limits are applied

Note that a scaling factor is used to bring the different variables (in different units) to a common scale (0-1 or 0-100), and any variation from the target value for each criterion is penalized by an individual weighting factor, which can be different above and below the target value.

A.4 Reference point method - an energy planning model for Vienna

Energy planning is a general term that is applied to a variety of issues. It can address, for example, the design of energy supply and utilization in new buildings; it can also address municipal planning of district heat supply and the structure of heating systems. In national energy planning, the focus is on political targets such as a diversification of energy sources or environmental targets such as a reduction in acidification of soil and lakes.

The public utility of Vienna used the dynamic linear programming model MESSAGE [6] for its energy plan to evaluate the future development of the municipal energy system, especially with respect to the coordinated expansion of the gas and district heat grids. The organizational structure is such that electricity, district heat, and natural gas are handled by three players in the energy market of Vienna.

A multi-objective approach was natural in the more long-term planning problems of energy systems. The model for Vienna has been set up as a multi-objective optimization model ensuring that three objectives are minimized: system costs; energy imports; and pollutant emissions (using an aggregated index for various pollutants, which is generally applied in Vienna). A simple aggregation of these objectives into one is not possible; for example, although energy imports can be counted as costs, the dependence on imported energy is a separate issue and it is difficult to convert this objective into monetary units; the same concerns pollutant emissions.

A.4.1 The substantive model

The dynamic linear programming model MESSAGE [6]. The variables of MESSAGE were grouped into three categories:

1. Energy flow variables representing an annual energy flow quantity. The unit is usually MWyr for small regions and GWyr for bigger areas
2. Power variables representing the production capacity of a technology (usual unit: MW or GW)
3. Stock-piles representing the quantity of a fuel being cumulated at a certain point in time (usual unit: MWyr or GWyr).

The constraints generated by MESSAGE were grouped into the following categories:

1. Energy flow balances modeling the flow of energy in the energy chain from resource extraction via conversion, transport, distribution up to final utilization
2. sum or relational constraints limiting aggregate activities on an annual or overall basis, either absolute or in relation to other activities,
3. dynamic constraints setting a relation between the activities of two consecutive periods
4. counters that are only used for accounting purposes.

A.4.2 The preference specification

The targets of such investigations differ depending on the scope of the problem and the decision makers involved. Industrial bodies and energy utilities strive for strategies with minimal costs. In this case other objectives, such as environmental or social aspects, are typically viewed as constraints. As an example, fuel use in a power plant can be constrained due to site-specific regulatory emission limits. However, that such constraints are actually soft therefore a classical way of their representation as (hard) constraints often results in various difficulties. This was the reason to apply the reference point approach which proved to be a very suitable analysis method for the energy planning in Vienna.

The *Reference Trajectory Optimization Method* is an approach to optimize more than one objective function for a problem in a way that circumvents the necessity to define weights for converting a multicriteria problem in the corresponding single criterion problem. The reference point approach allows the definition of reference trajectories for all objectives; the solution of the auxiliary parametric optimization problem lies on the Pareto-optimal border of the feasible region and is as close as possible to all reference trajectories.

From a methodological point of view, the results of the study show the usefulness of a multi-objective modeling approach. Especially, the applied reference point approach supports multi-objective problem analysis which proved to be much better than the classical single-criterion optimization-based approaches, including the most popular method of treatment of multicriteria problems through assigning weights to criteria. More details on this study can be found in [8].

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